FERTILIZER USE AND WATER QUALITY

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CONTENTS

Fertilizer Use and Water Quality[1]

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SUMMARY

This publication evaluates the role of nitrogen and phosphorus fertilizers in water pollution and summarizes the research on the complex relations between nutrient inputs and outputs.

Available data do not often permit making valid estimates of nutrient transfer from fertilizers to ground and surface waters. A reliable basis for evaluating the effects of fertilizers on water quality requires quantitative measurements of water inputs and behavior in agricultural watershed studies that encompass appropriate ranges in climatic and management conditions.

When virgin soils in the United States were first cultivated, many were rich in organic matter and plant nutrients. These soils provided far more nitrogen than the crops could use, and losses by leaching to water bodies or by denitrification to the atmosphere were large. As a result of cultivation, these natural supplies gradually diminished. By 1969, the use of almost 7 million tons of fertilizer nitrogen a year, as well as improved land use and management practices, was still not enough to compensate for the large yearly drop in the capacity of the soil to supply nitrogen.

Because nitrogen is highly soluble, many are quick to associate statistics on the rapid expansion of fertilizer use with suspected increases in water pollution from nitrates; however, the behavior of nitrogen in soil is highly complex. Besides the nitrogen added to soil in the form of fertilizers, one must consider the organic matter in the soil and the rate at which it is mineralized, the atmospheric nitrogen that is fixed either symbiotically or nonsymbiotically, the nitrogen involved in crop utilization and leaching, the nitrogen assimilated by micro-organisms, and the nitrogen returned to the atmosphere.

In the dynamic soil-plant system, these processes take place simultaneously. Thus, when nitrate is found in water, it is difficult to determine if fertilizers are the source. However, increased dependence on fertilizer nitrogen has created opportunities for creating a more favorable balance between nitrogen inputs and removals than previously was attainable.

Future opportunities for manipulating the nitrogen balance in agriculture depend on further improvements in the technology of fertilizer use based on research. Practical methods must be developed for assessing not only the current nitrogen-supplying capacities of soils but also the changes that result from fertilizer use. Such estimates, coupled with greater knowledge of nitrogen requirements of crops and of management practices needed for most efficient nitrogen use, can provide the basis for realistically predicting fertilizer needs of specific crops and meeting these needs effectively under different soil and climatic environments.

Phosphorus, on the other hand, when it is added to soil in the form of fertilizer, is rapidly immobilized through adsorption on clays or precipitation as iron or aluminum phosphates. Because of this low solubility, the loss of fertilizer phosphates in water is not significant, especially in relation to the quantities released from municipal and industrial wastes. Phosphorus additions to water bodies from agricultural lands are almost wholly associated with erosion. Thus, erosion control practices—which include high levels of fertilization to provide good plant cover—will tend to control water pollution from phosphorus.

Precise control of fertilizer use depends on gaining a better understanding through research of the behavior of applied nitrogen and phosphorus in soils. For example, leaching and runoff of nitrogen cannot be evaluated without a detailed understanding of water balance and water movement in soils. Also, the chemical and biological processes of immobilization, mineralization, and denitrification require further intensive study.

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Our ultimate goal should be the development of mathematical models that depict the integrated behavior of all components of the nitrogen cycle significant to agriculture and the associated environment.

NITROGEN

Evaluation of Current Knowledge and Technology

Introduction

The difficulty of distinguishing truth from half-truth is well illustrated in the conflicting evidence that has appeared in recent articles on the sources and role of fertilizer nutrients in water pollution. The present report was prompted by the need for an evaluation of these nutrients as a basis for testing the validity of conflicting public claims. Uncertainties and misunderstandings have arisen, often because conclusions were based on insufficient knowledge of the factors involved or their relative importance. A comprehensive evaluation of these divergent claims requires consideration of the balance between nutrient inputs (from soil and fertilizers) and outputs (crop removal, erosion losses, leaching losses, volatilization, and immobilization) as affected by cropping system, soil conditions and management, and climatic factors (principally water). In the final analysis, the nutrient balance and water balance for a particular situation must be defined before meaningful conclusions on disposition of nutrients in an agricultural system can be reached.

Great concern has been expressed regarding nutrient buildup in streams, lakes, rivers, and reservoirs, not so much because of the increased nutrient concentration, but because of its possible effects in promoting undesirably large growths of algae and other aquatic plants. In this connection, nitrogen and phosphorus are regarded as being of primary importance. Yet, the overall nutrient requirements of algae and various aquatic plants are only partially understood, as is evidenced by recent proposals for expanded research on this subject by the Departments of Agriculture and Interior.[3] Because of the present lack of knowledge, for example, we cannot state categorically that above-normal levels of nitrogen and phosphorus in waters will result, inevitably, in algal blooms. If another essential nutrient becomes a limiting growth factor, increasing concentrations of nitrogen or phosphorus conceivably would have little effect on growth of aquatic plants.

A high nitrate content in drinking water often causes concern for public health. High-nitrate water, when consumed by babies, may cause methemoglobinemia (10 parts per million of nitrate-N is sometimes considered to be the "critical" level for potable water). Potable waters in this country vary widely in content of dissolved salts. Usually, the dominant salts are chlorides, bicarbonates, and sulfates of calcium, magnesium, potassium, and sodium. Nitrate and phosphate usually are present in very low concentrations. The presence of high nitrate levels, particularly in well water from farmsteads, often has been attributed to contamination from animal wastes.

The relation of nutrients to water quality outlined above has been recognized for many years and has been discussed in detail by Wadleigh.[4] Further recognition of these systems and a discussion of Agriculture's responsibilities as well as those of other Departments in Government in defining and controlling these systems have been presented in a joint report of the U.S. Department of Agriculture and the Office of Science and Technology. The OST-USDA report is concerned with all the possible major sources of environmental contamination from agriculture, their relative significance, and needs for research and action directed toward their alleviation or control. In a section on "Plant Nutrients," the report calls attention to the steep rise in the use of fertilizers over the past few decades and emphasizes the need for clearer understanding of the effects of fertilizers on water quality.

None of the reports on agriculture-related pollution has considered, in detail, the problems of fertilizer use as it relates to the nutrient contents of water. It has been charged that fertilizers are increasing, measurably, the nutrient content of surface and subsurface waters, and that continued increases in fertilizer use will result in widespread buildup, particularly of nitrate, to intolerable levels. Others have expressed the view that effects of fertilization are unimportant today, and will continue to be, of little consequence, as long as fertilizer use does not exceed economically optimum levels.

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[3]Control of Agriculture-Related Pollution. A report to the President from the Secretary of Agriculture and the Director of the Office of Science and Technology, Washington, D.C. January 1969.

[4]Wadleigh, C. H. Wastes in Relation to Agriculture and Forestry. U.S. Dept. Agr. Misc. Pub. 1065, 112 pp. 1968.

The United States receives about 30 inches of precipitation each year. Approximately 22 inches is returned to the atmosphere as evaporation from soil, water, and plant surfaces; 8 inches, or a little over one-fourth of the total average annual U.S. precipitation, reaches the oceans via streams. Nitrate-nitrogen is carried by water flowing overland or percolating as subsurface flow through the soil and geologic materials and emerging as springs, seepage, and groundwater discharge.

Because nitrate ions move with soil water, information on the quantity and movement of water is required before we can assess and control leaching losses. The redistribution of water in a soil profile is a continuous, dynamic process. Data provided by a water balance covering a specific time interval may account for changes in soil water content arising from infiltrating rainfall or snowmelt and for losses from seepage, evaporation, and evapotranspiration. Upward movement of water from shallow groundwater tables by capillarity also must be taken into account.

On small, uniform fields receiving known amounts of precipitation and irrigation, an approximate water balance can be obtained by estimating evapotranspiration. In scheduling irrigation throughout the 17 Western States and Hawaii, seepage losses, which take into account the changes in soil moisture storage, are commonly computed as the difference between inflow (amount, duration, and frequency of irrigation and precipitation) and evapotranspiration.

Over larger areas, variations in topography, soils, land use, geology, and precipitation complicate the determination of water balances on agricultural watersheds. Determination of inflow-outflow relationships on hillslopes, for example, is complicated by lateral flows over or through the soils and geologic formations. Topography also influences precipitation and evaporation. The intake rate and storage capacity of the soils over a complex watershed may vary widely—from almost no intake on shallow rocky hillsides to many inches in well-drained residual or deep depositional soils. Deep alluvium along stream channels often absorbs much of the runoff from adjacent thin hillslopes.

Temporal difference and chronological sequences of precipitation, superimposed on the areal variations, add to the complexity of water balance determinations. In any case, the amount of water moving through the soil profile reflects the balance between evapotranspiration and amount, duration, and frequency of irrigation and/or precipitation.

One of the most complicating influences on the water regime of agricultural watersheds is man's activity in soil, crop, and water management. Fertilizer application and cropping practices can increase efficiency of crop water use. Manipulating agricultural lands and waters for crop production can greatly affect the disposition of water: Cutting forests can increase water yields; continuous cultivation of sloping lands and overgrazing of pastures can increase runoff losses; and artificial drainage can remove excess water from land.

The capacity of the soil to retain or transmit water depends basically on its porosity, texture, depth, and mineralogy as modified by numerous chemical, physical, and biological factors. Nitrate-nitrogen can be leached only when water in excess of soil retention capacity moves through the soil profile. If the water-holding capacity of the profile is near saturation, the water and nitrate are displaced to lower depths by incoming rainwater. If the soil is dry and water input is less than retention capacity, the nitrate may only be redistributed within the root zone.

Between rains or irrigations, the downward movement of water and dissolved fertilizer salts in unsaturated soils is slow because the water occurs as films around soil particles. The rate of movement becomes less as the soil dries and the water films become thinner and discontinuous. Movement is further slowed by interaction of the dissolved salts with clay surfaces. These charged interfaces attract both water molecules and plant nutrient ions, retaining them in the soil for use by plants while preventing loss by leaching. The extent to which this retention mechanism operates in a given soil depends primarily upon the kind and quantity of organic and inorganic colloids present and the nature of the plant nutrient concerned.

Crop plants influence the storage and movement of soil water in numerous ways. The above-ground parts of plants intercept raindrops before they reach the ground, preventing the formation of crusts which impede the intake of water by the soil. Plants also slow down the rate of overland flow, allowing more time for insoak. Roots are active not only in extracting water but also in opening channels for transmission of water into the soil. The water retention capacity and depth of the root zone profoundly influence water and nitrate movement within the soil profile. Different kinds of crops develop characteristic root patterns, ranging from shallow fibrous to deep taprooted plants. However, the basic rooting pattern of a particular plant species can be modified by the texture of the soil, the nature of the layers present, and the chemical status of the soil.

Plant Nutrients in Soil and Water

Of the 16 known plant nutrients, 13 can be supplied by the soil in varying degrees of sufficiency. The remaining three nutrients—carbon, hydrogen, and oxygen—are derived from air or water; various legumes obtain part of their nitrogen by fixation of atmospheric nitrogen. Often, nitrogen and potassium are more abundant in soils than all remaining soil-derived nutrients, i.e., phosphorus, calcium, magnesium, sulfur, and seven trace elements (essential micronutrients)—boron, iron, copper, zinc, manganese, molybdenum and chloride. Moreover, crops generally require more nitrogen and potassium than the combined total for the other soil-derived nutrients. As an example, a 150-bushel corn crop (roots, stover, and grain) may contain about 300 pounds of nitrogen, 250 of potassium, 50 of phosphorus, 60 of calcium, 30 of sulfur, 50 of magnesium, 3 of iron, 0.5 pound of manganese, 0.1 of boron, and mere traces of zinc, copper, molybdenum, and chloride.

The chemical composition and biological properties of water in a flowing stream are determined by all the various soils and geologic materials through which the water has moved. Runoff from adjacent land, seepage from underground strata, runoff from farmyards, domestic sewage, waste water from manufacturing plants, and irrigation return flow are examples of the diverse contributors of nutrients that affect the quality of water. Dissolved in water, of course, are many elements which are not essential to the growth of higher plants or algae. Some elements (for example, boron and lithium) may be present in amounts that repress the growth of living organisms. Much of the information on mineral nutrient composition of ground waters in recent years has been obtained from sampling wells. In 1961, a Nebraska survey of 1,100 wells showed that the upper limits in nutrient contents of 95 percent or more of the samples were as follows: Nitrate-N, 10 p.p.m.; phosphorus, 0.8 p.p.m.; potassium, 40 p.p.m.; calcium, 100 p.p.m.; magnesium, 60 p.p.m.; sulfur, 100 p.p.m.; and boron, 2 p.p.m. Variations in individual nutrient content were not clearly related in any instance to agricultural practices or amendments.

Plant Nutrients Supplied in Fertilizers

In 1968-69, the amounts of nitrogen (N), phosphorus (P), and potassium (K) contained in all fertilizers sold in the United States, respectively were 6.8, 1.9, and 3.2 million tons. In 1959-60, the tonnages of N, P, and K were about 2.8, 1.2, and 1.8 million; 10 years earlier, in 1949-50, they were 1.0, 0.85, and 0.95 million tons. The outstanding rate of increase in nitrogen use has caused concern about possible buildup of nitrate in water supplies. From 1950 to 1968, use of nitrogen increased about sevenfold, while phosphorus use approximately doubled, and potassium use slightly more than tripled. Although some concern has been expressed about the possible increases in phosphorus content of waters because of greater phosphorus fertilizer use, other phosphorus sources, particularly detergents, may be far more significant. Because there is no indication that further potassium enrichment of waters would enhance algal growth, there has been little concern about the role of increased potassium fertilization.

Most of the calcium and magnesium applied to soils is in agricultural liming materials. Substantial amounts of calcium and sulfur also are applied in calcium phosphates and as gypsum. The influence of these additions on chemical composition of water is negligible in comparison to effects of soils and their parent materials.

Micronutrients applied as fertilizer have little tendency to migrate in the soil and can be neglected in considerations of water quality. Moreover, the amounts used are small. In 1967-68, the amounts of micronutrients sold for fertilizer were as follows: Copper, 2,400 tons; iron, 3,260; manganese, 10,700; zinc, 14,500; and molybdenum, 80.

Fertilizer Use to Supplement Soil Nutrient Supply

Factors determining fertilizer need.—Overuse of fertilizers not only wastes exhaustible natural resources, but also enhances opportunities for adding an excess of certain nutrients to water supplies. From an economic viewpoint, the goal should be to control fertilization at levels that result in the most profitable returns to the farmer. Some would argue that even this level is higher than can be tolerated from the standpoint of water quality.

Several important factors must be taken into account before adequate fertilizer use can be achieved: (a) Potential crop yield under prevailing (most probable) environmental conditions: (b) the uptake of nutrient associated with this potentially attainable yield; and (c) the nutrient supplying capacity of the soil.

Obviously the difference between (b), nutrient content of the crop associated with a particular yield level, and (c), nutrient supplied by the soil, represents the amount of nutrient that must be taken up by the crop from

fertilizer. If this amount were known, there still remains the question: How much fertilizer actually must be applied to meet the needs of the crop for supplemental nutrient? The higher the fertilization level required to deliver the needed amount of nutrient to the crop, the greater will be the opportunities for losses affecting nutrient content of ground and surface waters. Thus a highly important goal in adequately meeting nutrient needs of the crop is to attain optimum efficiency of fertilizer use. The feasibility of controlling fertilizer use according to this general concept is discussed next.

Nutrient requirement of crop.—The yield of crop attained under a given soil-environment complex, assuming all nutrients to be adequate, is the resultant of all other factors that influence plant growth (e.g., crop variety, pests, water supply, timeliness and suitability of farming operations, and other management factors). Thus, the probability of attaining a given level of production for a given crop varies among agricultural regions and with management practices. Amount of nutrient uptake varies with attainable yield level of a given crop, and different crops have characteristic internal nutrient requirements. However, for a particular crop, the uptake of a particular nutrient per unit of dry matter (i.e., the percentage of nutrient) is essentially constant, even in the case of widely varying attainable yields resulting from different combinations of climate, soil, and management. The internal nitrogen requirement of corn, for example, based on near-maximum yields attainable in different areas and years, is close to 1.2 percent nitrogen in the total dry matter (grain plus stover). This percentage remains relatively constant (1.2 to 1.3), even with attainable yields varying by twofold or threefold or more. The value for different small grain crops varies from 1.0 to 1.3 percent. Two-year-old sugarcane contains about 0.2 percent nitrogen in the dry matter at maximum attainable yield, whereas sugarbeets (beets plus tops) contain about 1.8 to 2.0 percent. For certain crops, the nitrogen requirement associated with attainable yield is yet to be determined. As yields drop below the levels attainable, owing to deficiency of nitrogen, the percentage of this element in the crop drops below that associated with near-maximum requirement.

Based on the definition of internal requirement as given above, much more is known about the specific requirements for nitrogen in the various farm crops than is known for other nutrients. Nevertheless, data may be available in the literature to determine the internal needs for other nutrients with several of the commonly grown crops.

Nitrogen is the nutrient most subject to loss from the soil. Therefore, greatest attention will be given to the problem of controlling nitrogen fertilization. Because phosphorus seldom leaches from soils, it poses a different kind of problem and will be considered separately. The internal nitrogen requirement of crops has been discussed in some detail because of its fundamental importance in defining and specifying realistic goals for nitrogen fertilization. The concepts will be used later in considering present and projected fertilization levels in relation to nitrogen losses to the environment.

Nutrient-supplying capacity of soil.—The amount of fertilizer nutrient needed to satisfy optimum nutrient requirements in the crop is the difference between that required for a specified yield and the amount supplied by the soil. Numerous methods have been devised for assessing the nutrient-supplying capacities of soils. Most of these methods involve chemical extraction of some portion of the total soil nutrient. The usefulness of the method selected depends on how well extractable nutrient correlates with the actual ability of soils to deliver nutrient to the crop, or with the crop response to application of the nutrient in fertilizers. Certain of these procedures are now being used extensively in soil testing laboratories as an aid in predicting fertilizer needs, particularly for phosphorus and potassium and, to a lesser extent, for nitrogen and other nutrients.

Assessing the nitrogen-supplying capacities of soils poses a special problem, because conversion of soil organic nitrogen to plant-available forms (nitrate and ammonium) is accomplished largely by soil micro-organisms rather than by chemical dissolution or ion exchange, as with phosphorus and potassium. Biological methods have been devised for determining the relative capacities of soils to deliver nitrogen to the crop, but they have seen limited use because a week or longer is required to measure mineral nitrogen released through biological action. The problem of assessing nitrogen status of soils is further complicated by the presence in the soil of nitrate- and ammonium-nitrogen residual from previous fertilizer applications. As the use of nitrogen fertilizers increases, the importance of evaluating residual mineral nitrogen as well as the supplying capacity of organic reserves will become more and more evident.

Once suitable samples have been obtained from the field, the amounts of residual mineral nitrogen in soils can be determined with relative ease. Upon extracting and determining the mineral nitrogen, the problem still remains of determining how much additional nitrogen is potentially available from the organic reserves. Recently, the U.S. Soils Laboratory, Beltsville, Md., proposed a rapid extraction method for measuring relative availability of soil organic

nitrogen in different soils. This method appears to offer more promise than any of the chemical approaches yet devised. The method apparently extracts organic nitrogen forms readily susceptible to mineralization, and it provides for determining the amount of mineral nitrogen initially present in the soil as well as the amount of the readily mineralizable fraction of soil organic nitrogen. The next essential step will be to test the usefulness of the results obtained by this approach in predicting the need for nitrogen fertilization under field conditions.

The chemical or biological methods being used to assess nutrient status of soils are empirical and do not, in themselves, reveal how much nutrient will be removed from soil by plants. Their usefulness for this purpose depends on our knowledge of the relation between uptake of soil nutrient by the crop and amount of nutrient extracted by the soil test method. Once this relation is known for a given agricultural environment and crop, we can estimate reasonably the uptake of soil nutrient from the amount of nutrient extracted.

In a study of nitrogen uptake by sugarcane in Hawaii, an objective was to determine the relation between nitrogen uptake from soil in the field during the growth of the 2-year crop and amounts of nitrogen mineralized in the laboratory during a 2-week period of incubation. Field plots, without nitrogen fertilizer but adequately supplied with other nutrients, were laid out on several irrigated fields. Soil samples for mineralization studies were taken from each plot at the beginning of the 2-year cropping period. At the end of 2 years, sugarcane was harvested, weighed, and analyzed for total nitrogen. It was found that two units of nitrogen were taken up from the soil by sugarcane for each unit of soil nitrogen mineralized in the laboratory test. The empirical nature of this result in no way detracts from its usefulness, as long as it provides a reasonably accurate and consistent basis for estimating how much nitrogen the crop will derive from the soil. Without such knowledge, it is impossible to estimate how much additional nitrogen from fertilizer will be required in the crop.

Fate of Applied Nitrogen Fertilizers

Forms of nitrogen fertilizers.—The domestic supply of nitrogen for fertilizer purposes in the United States for 1967-68 was 6.8 million tons, distributed among various sources as follows:

	Percent
Ammonium nitrate	14.4
Ammonium sulfate	5.1
Urea	5.4
Other solids (ammonium phosphates, sodium nitrate, calcium cyanamide, and urea)	9.3
Liquid ammonia (including aqua ammonia)	51.0
Other liquids	14.8

The above figures indicate that about 90 percent of the fertilizer nitrogen used was in the form of ammonia or ammonium salts. This includes urea nitrogen, because of the fact that urea is hydrolyzed to ammonium nitrogen soon after being applied to the soil. The remainder of the nitrogen is largely nitrate (about one-half, or 7.2 percent, of the nitrate-nitrogen comes from ammonium nitrate fertilizers; less than 0.5 percent comes from sodium nitrate; and the remainder is probably from ammonium nitrate dissolved in liquid fertilizer).

Nitrogen fertilizer consumption for 1968-69 was within 1 percent of that in the preceding fiscal year. Thus, 1968-69 was the only year within the present decade not marked by a substantial increase in nitrogen consumption over the previous year.

Conversion of ammonium-nitrogen to nitrate-nitrogen.—Ammonium ions are positively charged and migrate very slowly in soils because the attractive forces of the negatively charged clays and organic colloids restrict their mobility. As long as the nitrogen stays in ammonium form, the possibility of nitrogen loss by leaching of water through the soil profile can be ignored. In normal soils, however, ammonium is converted to nitrate, a negatively charged ion, and this form can move much more freely in the soil water. It is this fact that gives rise to most of the concern that is being expressed about nitrogen in relation to water quality.

Ammonium ions are converted to nitrate ions in two steps, each requiring specific bacteria. In the first step, ammonium is converted to nitrite ion. Normally, the second step—conversion of nitrite to nitrate—occurs so rapidly that little of the intermediate form, nitrite, can be detected in water extracts of soils. Yet, under certain conditions, the conversion from nitrite to nitrate can be inhibited (e.g., high pH in the fertilizer application zone) and nitrite

ions can accumulate. The conditions favoring nitrite accumulations, however, are known and can be anticipated and controlled. Thus, the problem usually is of minor significance. In any case, however, dissolved nitrite and nitrate are subject to downward movement in percolating water.

The rate of nitrification becomes an important consideration if it results in large amounts of nitrate being present during periods when the crop has little capacity to take up nutrients or before the crop is planted, and if rainfall or irrigation water exceeds the soil storage and crop requirements. Nitrification rate is affected by temperature, soil moisture, degree of acidity or alkalinity, soil aeration, type of nitrogen fertilizer, and rate of application.

The optimum temperature for nitrification of ammonium ranges from 85° to 90° F, and the rate of nitrate production drops by about one-half for each 10° temperature drop, declining to almost 0 at 32°. In areas where soils are frozen during much of the winter, autumn application of ammonium fertilizers (after soil temperature drops below about 50°) often is recommended with the view that there is little probability of appreciable nitrification occurring before the next cropping period. Since conditions vary considerably from year to year and among agricultural regions, particularly in the interval between spring thaw and planting, there is no unanimity of opinion regarding the desirability of fall nitrogen application. Thus far, the question has been treated as an aspect of farm economics with inadequate attention being given to measurement of losses of fall-applied nitrogen.

Normally, nitrification is not considered to limit crop production, because plants can utilize ammonium nitrogen as well as nitrate nitrogen. Requirements for specific information on nitrate production rate, useful as a basis for predicting likelihood of nitrate leaching during cropping and between crops, have been heightened by the increased concern over more efficient use of nitrogen fertilizers, and more research will be required in this area.

Nitrogen losses in gaseous forms.–Most soil scientists believe that an appreciable amount of applied nitrogen may be lost in gaseous forms to the atmosphere. Most of the evidence that such losses occur has come from laboratory and greenhouse experiments and from outdoor lysimeter studies. Frequently, the initial nitrogen content of soil plus amounts of nitrogen added cannot be accounted for by amounts of nitrogen removed in cropping, leaching losses, and total nitrogen remaining in the soil. Use of nitrogen fertilizers tagged with the heavy isotope, ^{15}N, confirmed that losses of nitrogen from soil-fertilizer systems could occur. Elemental nitrogen gas, N_2, and certain gaseous oxides of nitrogen have been identified as by-products of the various biological and chemical alterations in soil.

Biological denitrification is considered to be one of the more important processes accounting for gaseous nitrogen loss from soils, and nitrogen, N_2, is believed to be the main gas produced. In the process, nitrate occurring in zones of poor aeration (e.g., waterlogged spots; and spots where oxygen is very low as, for example, in a clump of decomposing crop residue) is reduced to elemental nitrogen gas; the micro-organisms derive oxygen from the nitrate, NO_3, in the absence of free oxygen gas in the soil atmosphere. Under special conditions, nitrite accumulates in urea or anhydrous ammonia fertilizer placement zones, and the unstable nitrite may decompose and liberate gaseous forms of nitrogen. For this to occur, the pH in the placement zone must shift from alkalinity, which favors nitrite accumulation, to acidity, which is required for nitrite decomposition.

When ammonium salts are surface-applied to alkaline soils, considerable amounts of ammonia may be lost to the atmosphere. Application of ammonia in irrigation water to alkaline soils also is conducive to nitrogen loss. This is well recognized, however, and such losses are largely prevented by mixing or banding the fertilizer with the soil rather than by surface placement. Ammonia losses also may occur when urea is top-dressed on grass swards. Losses of nitrogen as ammonia are considered to be insignificant relative to denitrification losses discussed earlier.

Although this discussion indicates that much is known about mechanisms of gaseous nitrogen losses and the conditions under which such losses are apt to occur, little can be said regarding the extent to which losses actually take place under field conditions. Laboratory, greenhouse, and lysimeter studies indicate that losses in the range of 10 to 30 percent of applied nitrogen might well be expected. Losses of 30 percent are believed to be common in Illinois. As will be shown later, a knowledge of the magnitude of gaseous losses in field situations becomes a key factor in determining whether or not nitrogen fertilizer use at current and projected levels constitutes a water quality problem.

Biological and chemical immobilization of fertilizer nitrogen.– At least 90 percent of the nitrogen in soils exists in organic forms. A high proportion of the organic nitrogen is extremely resistant to microbial action. A portion of the nitrogen added to soil (e.g., nitrogen fertilizer, atmospheric nitrogen fixed by soil micro-organisms, and nitrogen deposited in precipitation) becomes immobilized in forms similar to those already existing.

Immobilization takes place in the course of plant residue decomposition by microbial action, during which soluble nitrogen is converted to organic forms. This is a dynamic system involving repeated cycles of nitrogen mineralization and immobilization. In the process, some of the soluble nitrogen forms produced by organisms (e.g., amino acids) apparently react with other soil constituents to add to the store of difficultly mineralizable nitrogen

comprising the bulk of soil organic matter. Tracer nitrogen, ^{15}N, has been used to show that the immobilized fertilizer nitrogen residual from previous cropping is very slowly available to plants, its rate of mineralization being about 5 percent each year. Of course, from the standpoint of nitrogen economy in soils, the important unknown is the amount of immobilization that actually occurs annually in a given cropping system and fertilizer regime. Few long-term field experiments have been done, using modern rates of fertilization, to determine the effects of continued fertilizer use on maintenance or buildup of organic nitrogen in soils under different systems of residue management. Greenhouse experiments often have shown 20 to 40 percent immobilization of applied nitrogen following one or more cropping periods.

Certain soils contain clay minerals capable of entrapping or "fixing" applied ammonium ions. When anhydrous ammonia is injected in soil, a portion reacts directly with certain organic constituents to form very insoluble ammonium complexes. Under field conditions, not much is known about the significance of either of these chemical mechanisms in nitrogen conservation, although their occurrence is well documented under laboratory conditions.

Efficiency of Fertilizer Use

The major nutrients.—Fertilizer efficiency as used here is synonymous with percent recovery of applied nutrient by the crop. Recovery of an applied nutrient is affected by numerous factors—nature of chemical reactions between soil and fertilizer, timing and placement of fertilizer, adequacy of other nutrients, and levels of other growth-modifying factors such as water and soil physical properties.

Efficiency of phosphorus fertilizer use by plants always is very low, largely due to the low solubility of phosphate-soil reaction products formed when soluble phosphates are applied. On phosphorus-deficient soils, it may be necessary to apply several times as much phosphorus as the crop takes up, to meet the internal requirements for the desired yield level. The residual fertilizer phosphorus accumulates, therefore, and reduces the subsequent application requirements for this element. Little can be lost except by soil erosion.

Most crops have high potassium requirements and use potassium fertilizers with relatively high efficiency, although the range in recovery of applied potassium is broad—e.g., 40 to 70 percent, or even higher. On all except very sandy soils, the residual potassium remains largely in the rooting zone. The portion that does not become fixed in clay minerals is mainly adsorbed in exchangeable form on surfaces of clay and organic colloidal material. Leaching losses, if any, take place slowly; hence, much of the residual potassium from fertilizers normally carries over to succeeding crops. Cumulative potassium recoveries from a given application, measured over several seasons, often exceed 90 percent. Some losses of potassium from soil occur in downward percolating water, as has been demonstrated in lysimeter studies. However, as far as can be determined, the concentrations of potassium in water supplies, although widely varying, constitute no threat to environmental quality. Moreover, the amounts derived from soils generally far outweigh amounts contributed by fertilizers.

Much is known about the factors that influence efficiency of nitrogen fertilizer use, although the manner in which they operate is not always clear. The range encountered in percentage recovery of applied nitrogen by crops is much wider than for other nutrients, whether considered on a local, regional, or national scale. Retention of unused nitrogen poses unique problems that have little in common with retention of phosphorus, potassium, and most of the other nutrients supplied in fertilizers or liming materials. Therefore, special attention is given in this report to the behavior of nitrogen fertilizer in soils as it relates to problems and questions that have been raised on water quality.

Timing of nitrogen fertilizer application.—The importance of timing nitrogen fertilizer applications to efficient nitrogen use by the crop has been demonstrated repeatedly in areas where the loss of applied nitrogen is prevalent. With irrigated corn in Nebraska, for example, use of summer-side-dressed ammonium nitrate was more efficient than either fall-applied or preplant ammonium nitrate. Unirrigated corn in New York showed a similar effect due to timing of application. With long-season crops (e.g., corn, cotton, sugarbeet, and sugarcane), efficiency often is improved by split applications if amounts of rainfall or irrigation, prior to extensive canopy and root development, exceed soil water storage and crop use capabilities. As an extreme example, nitrogen uptake, during the first year, from fertilizer applied to irrigated sugarcane in Hawaii, was 20 percent efficient when all the fertilizer was applied by planting and about 40 percent when one-quarter was applied at planting and three-quarters was applied at age 3 months. This kind of result is found only when losses occur from the root feeding zone before the crop is able to use the nitrogen. The highest efficiency in use of applied nitrogen will be achieved most often when the bulk of the fertilizer is applied during or just preceding the grand period of growth. Although this appears to be understood by most agricultural advisors, nitrogen application practices continue to be determined as much by considerations

involving convenience to the farmer and fertilizer sales organizations as by known principles of efficient nitrogen use. The fertilizer industry's efforts to promote fall fertilization, often backed up by recommendations of State agricultural advisors, explain why the practice is so prevalent. Furthermore, despite the losses that are apt to occur with off-season application of nitrogen, it often may be more profitable to the farmer to accept lower efficiency from fall fertilization or single preplant application when he considers the alternative costs of fertilizer, cost of special application equipment, and labor. Split applications timed to meet crop needs provide minimum opportunities for loss of nutrients from the rooting zone to water supplies.

Nitrogen Balance Sheet

Year 1930 vs. 1969.—Loss of nitrogen and other nutrients from cropland has been a problem of great concern in the United States since cultivation began. On newly cultivated lands, soil nitrogen for crop production was used very inefficiently, and nothing could be done about it. Ironically, least efficient use occurred on the most highly fertile soils (e.g., the midwestern high-nitrogen soils). The chief reason for this inefficiency was that cultivation stimulated mineralization of nitrogen in amounts that far exceeded crop use capacities. The excess nitrogen converted to mineral forms was largely dispersed to the environment by leaching and perhaps by denitrification. Moreover, additional large amounts of mineralizable nitrogen and other nutrients were redistributed or lost by erosion.

The greatest total loss of nitrogen and the periods of highest loss rates already were history by the time Lipman and Conybeare[5] made their estimates of nitrogen balance in U.S. agriculture. For the year 1930, they estimated that 4 million tons of nitrogen were lost by leaching and an additional 5 million tons by erosion (table 1). These losses were almost double the amount removed in 1930 by harvested crops (4.6 million tons). Nitrogen fertilizer use was only 0.3 million tons. Taking into account such additions as fertilizers, manures, and nitrogen fixation, an annual net loss of about 6.8 million tons of nitrogen was estimated for 1930.

What changes have occurred in the nitrogen balance picture in the intervening 40 years? Annual net loss of nitrogen to the environment is far less today than was estimated for 1930. It follows that overall efficiency of nitrogen use (both soil and fertilizer nitrogen) today is greater than was experienced in the years before World War II. From 1930 to 1969, combined annual losses of soil nitrogen by erosion and leaching probably declined by about 50 percent, or 3 million tons. Even the most unrealistic estimates of fertilizer nitrogen lost by leaching and erosion could not have reversed this trend.

By 1969, the annual use of nitrogen applied as fertilizers had risen to about 7 million tons, and the nitrogen removal by harvested crops had increased to 9.5 million tons. During the same period, however, soil nitrogen loss by erosion dropped by at least 2 million tons annually because of improved land use and management practices. In 1969, loss of soil nitrogen by leaching probably was 50 percent of that in 1930, because mineralization capacities of soils continued to decline during tne 40 years of intensive farming.

Generalizations of nitrogen inputs and loss or other dispositions, for the country as a whole, are not useful in considering nitrogen balance for restricted localities, because such views ignore variations in intensity of fertilizer use among agricultural regions and crops.

Current levels of fertilizer use.—Corn comprises about 21 percent of the harvested crop acreage in the United States, but receives about 41 percent of the total nitrogen fertilizer. In the Corn Belt, about 90 percent of the nitrogen used is applied to corn, which comprises about 40 percent of the acreage in harvested crops. It should be revealing, therefore, to consider the various components of the nitrogen balance sheet for corn under different levels of fertilization. Attention will be centered on the disposition of nitrogen under corn for current and projected levels of fertilization.

Nitrogen balance estimates require reliable data on (a) levels of corn production, (b) crop response to nitrogen fertilization, and (c) amounts of nitrogen taken up by the total crop (tops and roots) under specified conditions. For 1964, Ibach and Adams[6] compiled the information designated under (a) and (b), in cooperation with State soil fertility specialists, for agricultural regions and subregions throughout the United States. Uptake and recovery of applied nitrogen by corn were estimated from nitrogen contents of unfertilized and fertilized corn and from the associated percentages of maximum yield attained, as given in USDA Bulletin 431.

[5]Lipman, J. G., and Conybeare, A. B. Preliminary Note on the Inventory and Balance Sheet of Plant Nutrients in the United States. N.J. Agr. Expt. Sta. Bul. 607. 1936.

[6]Ibach, D. B., and Adams, J. R. Crop Yield Response to Fertilizer in the United States. U.S. Dept. Agr. Stat. Bul. 431. 1964, and Fertilizer Use in the United States by Crops and Areas. U.S. Dept. Agr. Stat. Bul. 408. 1964.

Table 1.—*Balance sheet of nitrogen (N) in the United States: Estimated changes from 1930 to 1969 on harvested cropland*

Item[1]	Amounts of nitrogen in—		
	1930[2]	1947[3]	1969
Inputs of nitrogen from:	*Millions of tons*	*Millions of tons*	*Millions of tons*
1. Fertilizer N	0.3	0.7	6.8
2. N fixed by legumes	1.7	1.7	2.0
3. N fixed (nonsymbiotic)	1.0	1.0	1.0
4. Barnyard manure	1.9	1.3	1.0
5. Roots of unharvested portions of crops	1.1	1.5	2.5
6. Rainfall	0.8	1.0	1.5
Total	6.8	7.2	14.8
Removals of nitrogen by:			
7. Harvested crops	4.6	6.5	9.5
8. Erosion	5.0	4.0	3.0
9. Leaching of soil N	4.0	3.0	2.0
10. Leaching of fertilizer N	0	0	?
11. Denitrification	?	?	?
Total	13.6	13.5	14.5

[1]Explanation of items:

1. Fertilizer N consumption for 1969 obtained from "The Fertilizer Supply, 1968-69." USDA, ASCS, Washington, D.C.

2. For soybeans, clover, alfalfa, and grass-legume mixtures, it was assumed that one-half of the N in harvested crops, in 1969, was derived from symbiotic fixation of atmospheric N.

3. No change from Lipman and Conybeare.

4. Assumes that 10 percent of manure produced was returned to cultivated land in 1969. (Mehring and Parks estimated that 15 percent was returned in 1947).

5. The ratio of Item 5 to Item 7 values as estimated by Lipman and Conybeare was assumed to remain nearly constant.

6. Gradual increases shown reflect the effects of atmospheric ammonia and nitrogen oxides associated with internal combustion engines and industry.

7. 1969 value based on estimates by W. C. White, "Plant Nutrient Toll: 1965 Harvest, USA", in Plant Food Review (Winter 1965), with adjustments for changes in total production of different crops, 1965-69.

8. Estimates of decreased losses of N by soil erosion reflect improved management practices.

9. Between 1930 and 1969, soil N depletion continued because of imbalance between N inputs and N removals by cropping and is reflected in the estimated gradual decline in soil N leaching losses.

10 and 11. See text for discussion of leaching and denitrification.

[2]Lipman, J. G., and Conybeare, A. B. Preliminary Note on the Inventory and Balance Sheet of Plant Nutrients in the United States. N.J. Agr. Expt. Sta. Bul. 607. 1936.

[3]Mehring, A. L., and Parks, R. Q. Agricultural Chemicals, v., No. 10, pp. 36-50; No. 11, pp. 33-39 and 77-78 for estimates of items 1, 4, and 7.

In Iowa, most of the applied nitrogen was taken up by crops. In the five agricultural subregions of Iowa, average amounts of fertilizer nitrogen applied to about 8 million acres ranged from 50 to 80 pounds per acre (average, 66 pounds per acre). In 1964, the weighted average amount of fertilizer nitrogen not accounted for by crop removal was 16 pounds per acre of fertilized corn (range, 8 to 34 pounds per acre). The fate of this residual fertilizer nitrogen is unknown. The important questions, relative to its effect on nitrate content of water, are: (1) What proportion of the unharvested nitrogen is converted to gaseous forms and escapes to the atmosphere (denitrification)? (2) How much becomes immobilized by reaction with soil? (3) What proportion leaches below the root zone and into the groundwater?

Even a conservative estimate of loss by denitrification from mineralized soil nitrogen and applied fertilizer nitrogen will account for much of the leftover nitrogen in the Iowa example. Fertilizer nitrogen plus mineralized soil

nitrogen made available to the crop ranged from 150 to 200 pounds per acre. Thus, a denitrification loss of as little as 10 percent of the mineral nitrogen would easily account for all of the nitrogen not taken up by the crop. Little or no nitrogen, therefore, would be susceptible to loss by leaching or immobilization. By most conservative estimates, nitrogen immobilization and denitrification together account for the calculated amounts of residual nitrogen, leaving none for leaching. There is little reason to doubt the validity of the approach discussed above in estimating the quantity of unaccounted-for nitrogen. The disposition of the excess nitrogen under diverse situations, however, is relatively unknown and difficult to predict based on present knowledge.

Fertilization at optimum levels.—At current levels of nitrogen fertilization for corn, there appears to be little or no possibility of increasing nitrate contents of groundwater, provided application is made according to accepted management principles that result in maximum attainable levels of fertilizer use efficiency. The main concern, however, is the extent to which continued increases in fertilizer use will raise existing concentrations of nitrate in waters. Specifically, concern is centered on the likelihood of or opportunities for leaching losses when nitrogen is applied at economically optimum levels. A realistic examination of the problem must be based on measurements of nitrogen recovery by the crop at appropriate levels of fertilization. While many field experiments have been conducted to determine economically optimum fertilizer rates for various crops as determined by yield of crop, few such experiments have included determining the nutrient uptake associated with the optimum yield.

Results from two Nebraska field experiments on corn serve to illustrate the possible magnitude of unaccounted-for nitrogen under near-optimum levels of nitrogen fertilization. In these two experiments, designated as A and B, corn grain yields at optimum fertilization (160 and 100 pounds N per acre, respectively) were 133 and 123 bushels per acre. Soil B supplied about twice as much nitrogen as did soil A. By season's end, amounts of nitrogen unaccounted for by plant uptake for A and B, respectively, were 45 and 50 pounds per acre, or about 19 and 21 percent of the nitrogen (fertilizer plus soil nitrogen) made available to the crop. Again, one can only speculate regarding the fate of this residual nitrogen. As was found in the case of suboptimum fertilization, the amounts of nitrogen involved might easily be dissipated by denitrification or immobilized through biological or chemical action.

Proposed Areas of Continued Research

Objectives

The following proposed areas of emphasis in continued research are aimed at achieving more effective use of nitrogen fertilizer.

1. Develop improved methods for assessing the nutrient status of soils and plants as a basis for controlling nitrogen fertilizer use.
2. Determine the behavior and fate of fertilizer nitrogen and soil nitrogen as influenced by management and environmental factors, with particular emphasis on fertilizer use at optimum and higher levels.
3. Improve efficiency of nitrogen use through definitive evaluation of methods for utilizing various nitrogen sources under the range of soil management and crop production systems, climate, and water regimes encountered in the field.
4. Develop and evaluate models of nitrogen behavior in the soil-plant system applicable to a broad range of agricultural conditions.
   a. Individual fields with measurable and controllable inputs of water and nitrogen.
   b. Watersheds with varying inputs of water, but providing for controlled nitrogen supply.

Justification for Research

Objective 1: Nutrient status of soils and plants in relation to nitrogen fertilizer use.—Early recognition that cultivation of soils was accompanied by substantial losses of nitrogen and other nutrients prompted intensive research effort aimed at devising management systems to conserve fertility and productivity of soils. Results from numerous long-term field experiments and associated laboratory studies demonstrated the inevitability of nitrogen decline under cultivation, and provided important basic information on the nature of chemical and biological changes in soil nitrogen that take place under cropping. This early research, however, contributed little to an understanding of impending problems associated with intensive nitrogen fertilizer use.

Following World War II, many short-term field experiments were conducted on widely differing soils to determine the effects on crop yields of applying nitrogen. The striking yield responses obtained prompted a sharply rising trend in the use of fertilizers that has continued up to the present time. Information gained during this relatively brief period provided empirical bases for recommending nitrogen application rates. In some instances, refinements in making recommendations on different soils were accomplished through correlation of crop response to nitrogen with indexes of soil nitrogen availability, but this approach has not been widely accepted, principally because of limited success in the development of reliable soil nitrogen indexes and their interpretation.

The present systems used to make nitrogen fertilizer recommendations are inadequate. Although these systems often provide for adequate use of nitrogen, they offer little insurance against overuse of nitrogen or the possibility for nitrate buildup in surface and underground waters.

Farmers have achieved remarkable success in raising levels of crop production through use of nitrogen fertilizers. If there were no concern regarding the adverse effects of overuse of nitrogen on water quality and, in some instances, on quality of food and foodstuffs, it is possible that extensive refinements of existing procedures for recommending nitrogen fertilization involving soil tests, plant analysis, and other criteria could not be easily justified on the basis of potential economic benefits. Existing circumstances, however, fully justify and, in fact, demand an intensive research effort aimed at devising more effective means of controlling application rates of nitrogen fertilizer within reasonable bounds and of achieving more efficient use of nitrogen in agriculture.

Objective 2: Behavior and fate of nitrogen in soils.—Much of the existing experimental evidence regarding disposition of nitrogen in soils was gained from studies conducted prior to the advent of high-nitrogen fertilization. The difference between known inputs of nitrogen (in rainfall, fertilizer, manure, and through biological fixation of atmospheric nitrogen gas) and measurable losses (principally by crop removal and in drainage water), as determined from lysimeter and greenhouse pot experiments, usually indicated losses of nitrogen from the system. These unaccountable losses, sometimes confirmed in measurements of total soil nitrogen before and after the experiment, usually have been attributed to denitrification.

Denitrification

A summary of nitrogen balance experiments indicated that a greater deficit occurred under growing crops than from fallow, the average losses of mineral nitrogen being about 20 percent with cropping and 10 percent with fallow. Lysimeter experiments in Illinois gave average nitrogen losses of about 30 percent, a value which frequently is mentioned in connection with nitrogen fertilization in that State. As previously pointed out in this report, substantial amounts of applied fertilizer nitrogen cannot be accounted for in crop removal (tops and roots). A question was raised regarding the possible role of denitrification in disposing of the residual mineral nitrogen. If unused nitrogen is lost back to the atmosphere by denitrification, it cannot, of course, contribute to nitrate accumulation in water. Under actual farming conditions, it has not been possible to determine the intrinsic importance of denitrification. Until the likelihood and extent of denitrification losses under field conditions can be predicted and verified from measuring pertinent soil characteristics, agriculture will remain in the vulnerable position of being unable, in many instances, to account definitely for the portion of applied nitrogen not taken up by the crop.

Immobilization of fertilizer nitrogen

Many agriculturalists believe it is very difficult, if not impossible, to avoid a decline in soil nitrogen under systems of intensive cropping. This view stems from results derived in the long-term rotation-fertility experiments conducted before nitrogen fertilizer use became of major importance. During the period of sharply rising nitrogen fertilizer use in the past three decades, meager evidence has been gained regarding the effect of sharply rising nitrogen fertilizer use on the nitrogen status of soils. The problem of nitrogen immobilization and accumulation is important because of its implications relative to (a) the changing requirements for fertilizer application and (b) the retention, in nonleachable forms, of residual fertilizer nitrogen not taken up by the crop. Hence, the link with water quality control is evident.

Nitrogen immobilization in soils is a result of chemical and biological reactions. The better known chemical reactions include (a) ammonium fixation by clay minerals; (b) ammonium fixation by lignin-derived substances in

soil organic matter; and (c) reactions of amino acids—derived from plant materials and microbial synthesis—with quinones and subsequent polymerization. Nitrogen immobilized by these mechanisms is relatively inert, i.e., slowly available.

Biological immobilization accompanies decomposition of plant residues from previous crops and mainly involves the synthesis of organic compounds by microbial action. Decomposition is a dynamic process involving concurrent immobilization and mineralization, i.e., nitrogen "turn-over." Hence, decomposition has a transitory effect on levels of nitrate nitrogen in soil. For example, decomposition of low-nitrogen straw residues in soil may deplete, temporarily, the mineral nitrogen, even to the point of depriving growing plants of an available nitrogen supply. Following the initial flush of rapid decomposition and biological nitrogen immobilization, however, biological activity diminishes, owing to depletion of readily decomposable substances. In time, immobilization occurs at a slower rate than mineralization, and a portion of the nitrogen becomes available for the growing crop.

The complexity of nitrogen immobilization reactions in soil is suggested from the brief treatment given above. The significance of these and other reactions in relation to nitrogen buildup under high fertilization regimes is poorly understood. Studies on the influences of soil properties (e.g., type and content of clay minerals, soil pH, and microbial populations), management systems (e.g., types and amounts of returned residues, tillage methods, and timing and rate of fertilizer application), and climate (particularly in reference to water regime) merit particular emphasis in continued research. Nitrogen fertilization of corn illustrates one aspect of the problem. For example, the effect of annual high-nitrogen fertilization on nitrogen immobilization in soil under continuous corn is relatively unknown. It seems highly unlikely, however, that large annual applications of nitrogen (200 to 300 pounds per acre) could be continued for many years without altering the nitrogen-supplying capacity of soil. In the interest of conserving nitrogen (i.e., minimizing leaching), application rates may need adjustment to take into account changes in cumulative residual effects. But, first, the problem must be defined through appropriate research.

Downward leaching of nitrate

An understanding of the movement of nitrate anions in soil requires an equally clear understanding of factors affecting water movement. It already has been emphasized that the amount of water passing through a given thickness of soil reflects the difference between total water inputs and the water lost by evapotranspiration and runoff or retained in the soil profile.

Water flow through soils occurs in response to gravity or gradients of water potential. The rate of flow depends on the magnitude of the driving force and on the conductivity of the medium. Both of these quantities are extremely difficult to measure accurately, even in the laboratory. Our understanding of water and nitrate movement will be greatly enhanced by the development of practical field methods for measuring water flow and the factors known to affect it.

Where water is largely subject to control, as in irrigated areas of negligible rainfall, considerable progress has been made in devising means for predicting when to irrigate and how much water is required to replenish that removed from the rooting zone by evapotranspiration. Where water is plentiful, there is a tendency to overirrigate, particularly if the system gives nonuniform water distribution. Under irrigation, therefore, it is important to determine the consequences of exceeding optimum water requirements, not only from the standpoint of water conservation, but also in relation to nitrate leaching.

Under a rapidly growing crop, where mineral nitrogen is taken up rapidly, the problem of nitrate leaching is minimal, even if excessive water passes through the soil during periods when little nitrate is present. This fact may lead to a false sense of security in considering the likelihood of leaching losses. The critical period when nitrate is most susceptible to downward leaching is the interval between harvest and the next growing season. Under summer fallow, in areas characterized by low rainfall, leaching of accumulated nitrate may occur during periods when rainfall exceeds water storage capacity and evaporative losses. In areas where soils remain unfrozen and winter rainfall occurs, the need for nitrogen fertilizers at the beginning of the growing season varies directly with the amount of rainfall during the preceding winter.

In areas where heavy nitrogen fertilization is coupled with abundance of water supplied by irrigation or rainfall, it is easy to demonstrate losses of nitrogen by leaching. In Hawaii, for example, extreme leaching losses of nitrogen have been shown to occur under sugarcane. The lost nitrogen, however, seldom enters into aquifers or surface reservoirs used for drinking water or recreation. Hence there are no problems in the usual sense, except those involving the economics of fertilizer use and the effects of nitrogen on the quality of millable cane. The pressing

demand for research is in areas where the likelihood of nitrate leaching is extremely variable because of primary dependence on rainfall for water. In the highly fertilized, nonirrigated sections of the United States, particularly where corn and cotton are grown, no systematic, reliable procedure has been developed for predicting when leaching losses are likely.

Objective 3: Efficiency of nitrogen fertilizer use.—Nitrogen is mobile in soil water and susceptible to leaching under conditions specified elsewhere in this report. Particular attention in research should be given to evaluating soil and water management factors that minimize the opportunities for nitrogen losses during the season of application and maximize the carryover of residual nitrogen to succeeding crops.

The time of nitrogen fertilizer application is believed to exert a large influence on percentage recovery of applied nitrogen in those areas where clearly definable opportunities for loss by leaching exist during and between cropping seasons. The influence of time of application on loss by denitrification is unknown. A large number of field experiments that compare "autumn with spring" or "single with split" applications, have led to conflicting interpretations of results in agricultural areas subject to rather wide fluctuations in amount and seasonal distribution of rainfall from year to year. Part of the difficulty has arisen from failure in most experiments to measure uptake of nitrogen by the crop as a function of application time. Yield response to nitrogen often has been the chief criterion used in interpreting time-of-application effects.

An example will suffice to illustrate the difficulty of interpreting time-of-application studies solely on the basis of crop yields. Suppose, for example, that the objective is to compare autumn and spring application of nitrogen fertilizer to corn, using 100 pounds of nitrogen per acre. Yield with no nitrogen applied was 70 bushels per acre, and 100 bushels per acre with both fall- and spring-applied nitrogen. Assume that 30 percent of the fall-applied nitrogen was lost between autumn and spring but that no loss occurred with spring application, which left 70 and 100 pounds per acre, respectively, for the crop. In either case, there still was more than enough nitrogen fertilizer to produce the additional 30 bushels of corn, even if the nitrogen present at planting were only 50 percent effective. Adequacy of nitrogen in the crop for both of these treatments would have been revealed by analyzing the crop for nitrogen content. Indication of greater nitrogen loss from fall application might have resulted from comparing the vertical distribution of mineral nitrogen during the growing season. Future evaluations of nitrogen treatments in field experiments should include the cumulative water balance for the experimental period as well as pertinent measurements other than yield. Otherwise, the results can hardly be expected to justify the large cost already involved in the central experiment.

Other controllable aspects related to effectiveness of nitrogen fertilizer use and requiring additional research include (a) source of nitrogen; (b) placement of N; (c) residue management; (d) liming and other nutrients; (e) use of cover crops between main crops to conserve residual nutrients; and (f) water management under irrigation.

Objective 4: Models of nitrogen behavior in the soil-plant-water system.—The ultimate goal is optimum use of our water and nutrient resources. This goal can be achieved only if we can predict the response of the whole system under the enormous variety of environmental conditions. The most feasible approach appears to be the consolidation of the numerous individual processes into a mathematical model. Modern computers can then be used to simulate the system under any of the desired conditions.

Yield of crop attainable in any given situation depends on many variable and interacting factors that influence growth. The literature contains numerous reports that permit fragmentary evaluations of plant growth in relation to nutrient uptake, soil properties, climate, and management. For specific agricultural situations that encompass a definable and limited range of crops, soil, and climate, it may be feasible to devise a mathematical model depicting growth and nitrogen uptake in relation to governing or determinative factors (e.g., water, other nutrients, and temperature).

The dynamic behavior of nitrogen in the complex soil-plant-water system cannot be understood until the factors known to affect its chemical and biological transformations and movement are integrated. A suitable model permits realistic prediction of nitrogen behavior when the variables are manipulated within the desired range. While it may not be possible to fully realize such an ideal result, the integrative processes involved in evaluating the components of a model, modifying the parameters, and testing the validity of various assumptions can provide an important framework or basis useful in establishing future research objectives. Because a large number of alternative hypotheses may be investigated readily by computer, it seems reasonable that the model approach should aid in eliminating certain invalid assumptions, in developing new ideas, and in focusing attention on factors meriting additional research effort.

Hydrologists have developed useful models for simulating many aspects of agricultural watershed performance. These models encompass the flow processes incurred as precipitation moves through the soils, plants, geologic formations, and channel systems to emerge as streamflow or as vapor returned to the atmosphere. In the distributive system of modeling, the landscape is incremented into response units whose integrated performance determines the response of the whole system to precipitation inputs. Individual soil-cover complexes are grouped to provide units which are hydrologically homogeneous for computations of water storage and flow. The topographic sequence of these units is compatible with the hydraulics of flow, and the units also appear to be adaptable to considerations of nitrogen behavior in watershed systems.

Soils of the uneroded upland or bottomland zones of a watershed, for example, constitute source areas for leachates for two reasons. The inherent capability of these areas for sustained intensive crop production dictates that they will receive the greatest inputs of commercial fertilizers. Because of their desirable physical properties, these are also the areas where infiltration rates will be relatively high and where opportunities for leaching will be greatest. This is in sharp contrast with other areas in the watershed where erosion hazards or other limitations confine the land use to meadows or forests which receive little or no applied nitrogen. Water balance and leaching on forests and meadows would also be quite different from that on the cultivated areas. Thus, research, upon which to base mathematical models for water and nitrogen behavior, should be continued on methods of defining source areas for water and nitrogen movement within agricultural watersheds.

Research Proposals

Numerous studies related to the objectives presented earlier are underway in the Soil and Water Conservation Research Division (SWCRD) and State experiment stations. The proposals to be discussed in this section call attention to research areas where more intensive study is needed and suggest certain approaches that seem to deserve special emphasis. There is no intent to detract from the importance of the information derived from past research or the great impact it has had on crop production. However, many of the previous studies evidently did not provide the kind of data so urgently needed today in evaluating the influence of adequate to excessive fertilization on nutrient content of water. Emphasis in earlier field experiments was placed on determining ways of achieving "balance" of nutrients and eliminating nutrient deficiencies. In a large percentage of the experiments, crop yield was the sole criterion used in evaluating the results. Future research must provide the basis for more comprehensive evaluation of experiments, and hence, will involve fewer but more intensive investigations. This view is emphasized in the discussion that follows.

Objective 1: Nutrient status of soils and plants in relation to nitrogen fertilizer use.—The feasibility of developing laboratory methods useful in assessing the relative potential nitrogen supplying capacities of soils has been demonstrated. A rapid chemical method for measuring potential soil nitrogen availability, developed recently in the U.S. Soils Laboratory, merits field evaluation. Such evaluation can be facilitated by cooperative effort involving the various research centers in SWCRD. Initially, the effort would be concentrated on establishing the relation between soil nitrogen availability index and uptake of soil nitrogen for each of the major crops.

In brief, the effort at selected locations would include (a) site selection (often this might simply involve using existing nitrogen fertilizer experiments); (b) soil sampling (as a minimum, preceding and following the cropping season); (c) measuring residual mineral nitrogen in the soil samples; (d) determining the potential nitrogen mineralization capacities of the soils by biological and chemical methods; (e) plant sampling for determining total nitrogen uptake of the mature crop (with certain crops, e.g., cotton, sugarbeets, and sugarcane, additional chemical analyses of selected plant parts or whole plant may be considered an important adjunct in defining nitrogen status of the crop); (f) measuring water inputs and calculating water balance for the experimental period; and finally, (g) collecting data from all sites and analyzing them as a unit.

The significance of information derived from such a study would not be limited to its direct use in reaching the primary objective. The study would provide information applicable in refining and developing models of nitrogen behavior in soil-plant systems (Objective 4) and in further understanding problems of nitrogen use as depicted under Objectives 2 and 3. Following analysis of data from the first year of study, cooperators would determine the feasibility or desirability of additional effort, its extent, and procedural modifications.

Objective 2: Behavior and fate of nitrogen in soils.—Various aspects of nitrogen behavior in soils have been investigated extensively in SWCRD and in several State experiment stations. As already emphasized, however, the steadily rising use of nitrogen fertilizers has created an urgent need for more definitive research efforts on nitrogen

behavior and disposition in soils in relation to water quality. Although limited research of this general nature is in progress, we need to expand research on denitrification, nitrogen immobilization or retention in soils, mineralization-immobilization relationships, and nitrate leaching.

Interpretation and application of much of the past research has been limited not only by the low levels of nitrogen often used, but, even more important, also by the inability in most instances to distinguish between soil and fertilizer nitrogen in the system. Thus, future research should emphasize use of tagged nitrogen (nitrogen labeled with the heavy isotope of nitrogen, ^{15}N), both in laboratory and field studies. Sharing of facilities for tagged-nitrogen research may be required to extend the use of this research tool.

Objective 3: Efficiency of nitrogen fertilizer use.—The abundance of relatively low-cost synthetic nitrogen has encouraged farmers to apply nitrogen fertilizers at rates that assure adequacy for attainable yields. This situation has not tended to foster interest in or support for research aimed at limiting consumption of fertilizer through more efficient use. As a result, present information is inadequate on percentage recovery of applied nitrogen by crops in relation to the various alternative management practices. The problem of water quality and fertilizer use concerns only the portion of nitrogen not recovered in the crop. Future experiments, therefore, should provide for determining (a) total nitrogen in the harvested crop; (b) assessing the nitrogen status of soil before and after each crop, including both mineral and potentially mineralizable nitrogen; and (c) water balance (evapotranspiration and runoff versus rainfall and irrigation) to evaluate leaching losses of nitrate. Nitrate distribution in the soil profile should be measured at appropriate times to establish significance of observed patterns of water balance. The interval between crops should be included in crop fertilization studies because, in many instances, this is when excess nitrate is most vulnerable to loss in percolating water.

In view of the conflicting viewpoints and uncertainty regarding the advisability of applying nitrogen during the fall or winter preceding spring-planted crops in humid-region agriculture, this problem deserves special emphasis in field studies. Experiments are needed, for example, to compare autumn, spring, early-season sidedressing or topdressing of nitrogen, and varying application frequencies. Carefully conducted studies covering a broad range of soil and climate should provide measurements essential in interpreting observed treatment differences.

Objective 4: Models of nitrogen behavior in the soil-plant-water system.—Model construction is considered to be an essential aspect of data analysis and interpretation. Mathematical models are designed to predict quantitatively the consequences of altering selected variables in a prescribed system. The basic relationships required in constructing a model for the dynamic soil-plant-water-climate system are derived from experimental data. Because research information is inadequate, first attempts at integrating the complex chain of events by means of a model must be met with limited success, if accurate prediction is the sole criterion. A systematic approach to modeling the system undergoing study will emphasize weakness in existing data and will aid in generating ideas for future research needed to improve the applicability of the model.

The value of a model designed to integrate related events can best be appreciated when its usefulness in making predictions has been demonstrated. As an example, considerable success has been achieved in devising a model for predicting irrigation requirement and scheduling on a practical field basis[7]. The model determines irrigation needs by integrating data on water consumption by crops based on certain meteorological data and such pertinent soil information as water storage capacity and infiltration rate. The irrigation model is being expanded with a view toward integrating nitrogen transformations, nitrate movement, and water behavior in the system. One of the goals n such research is to improve the basis for controlling nitrogen fertilizer use so that nitrate losses in return flow and ubsurface drainage are minimized.

Objectives 1, 2, and 3 emphasize the need for integrating measurements of the water balance with studies of ssociated nitrogen behavior. The ultimate goal is to develop models that depict water-nitrogen relationships. Data equired for these models can only come from appropriately designed field and laboratory experimental programs.

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[7] Jensen, M. E. Scheduling Irrigation with Computers. Jour. Soil and Water Conserv., v. 24, pp. 193-195. 1969.

PHOSPHORUS

Current Knowledge and Research Needs

Introduction

The belief that nitrogen and, to a greater degree, phosphorus are the nutrients that control or limit the growth of algae and other aquatic life, including fish, has focused much attention on these elements. Other nutrients are generally considered to be present in concentrations sufficient to meet the biological requirements for optimum growth. However, not enough is known of the nutritional requirements of algae or phytoplankton and how these requirements are influenced by environmental factors such as temperature, light levels, carbon dioxide and oxygen supply, and acidity. Furthermore, nutritional and environmental requirements of algae may vary even among species within a class. Hence, attempts to diagnose degrees of deficiency or toxicity of most of the elements, based on their concentrations in water, would be largely speculative.

It is often stated that the critical limiting concentration of phosphorus for the growth of blue-green algae is very low (below 0.01 p.p.m. P), and that concentrations of 0.05 p.p.m. provide quantities sufficient for profuse growth. Assuming the validity of these levels, the rate of algal growth is still governed by any essential factor that may be limiting. To assess algal growth potential in terms of phosphorus concentrations in water alone could be misleading. Since phosphorus requirements are so low, consideration should be given to other controlling factors. Nevertheless, in view of the emphasis on phosphorus, we must endeavor to correctly evaluate the contribution of agriculture to the phosphorus content of water resources.

Over the past 20 years the use of phosphates has increased markedly. In addition to the rise in use of phosphate fertilizers, there has been an even more rapid growth in the use of soluble pyrophosphates in detergents. The annual consumption of the latter now represents a per capita phosphorus use of about 4 pounds in the United States. Unless sewage treatments specially designed to remove phosphates are applied, urban areas can contribute available phosphorus to the environment at an annual rate of 2 tons per 1,000 persons in sewage effluents containing concentrations up to 5 p.p.m. of phosphorus. This enrichment of the environment is in addition to that contributed by agricultural sources.

Current Knowledge on Agricultural Phosphorus

Phosphorus and soil erosion.–The most direct way in which agricultural phosphorus moves into drainage waters is by erosion of the soil material on which it is adsorbed. The phosphorus content of agricultural soils (surface 6 inches) varies widely, ranging from almost none to several thousand pounds per acre. The average annual rate of application on U.S. cropland is close to 20 pounds per acre, although on certain crops, notably tobacco and potatoes, the rate is two or three times this amount.

Several studies have shown that phosphorus losses from cropland are caused entirely by erosion. Owing to the sporadic character of erosion and the variability of soil composition, no precise statement can be made about the general rate of this type of phosphorus movement, but some broad estimates are possible. Experiments with cotton and corn in Virginia showed a loss of 5 tons per acre of soil containing 1,000 p.p.m. of phosphorus. This represents a loss of 10 pounds of phosphorus per acre per year. Under high erosion, the loss may reach 30 to 50 pounds. Of the phosphate adsorbed on the soil colloids, only a fraction will be available for growth of aquatic plants—perhaps no more than 10 percent. Available phosphorus in lakes and rivers from fertilizer and soil phosphorus seldom exceeds 1 to 5 pounds per acre per year.

The chemistry of phosphorus in water.–Direct measurement of the total phosphorus concentration, including that on the suspended mineral material, is not a useful measure of the amount available for plant growth. Most of the phosphorus is inert, i.e., dissolves very slowly. The reactive surface-adsorbed fraction usually comprises less than 5 or 10 percent of the whole. Thus, the amount of biologically active phosphorus is a small fraction of the total in sediment-laden stream waters. For example, water containing a sediment load of 0.01 percent by weight, with 1,000 p.p.m. of phosphorus in the sediment, would have a total phosphorus concentration of 0.1 p.p.m.; however, the amount in true solution might be 0.01 p.p.m. or less. Settling out of the sediment will carry down considerable amounts of phosphorus that may be resuspended in the upper water under storm conditions.

Up to 50 percent of the total phosphorus in a surface soil may be present in organic forms. Little information is available on the biological activity of organic phosphates in streams, and new analytical procedures may be necessary to reveal its true significance.

Research Requirements

The primary objective of the research program should be to examine the physical and chemical factors that control the movement and availability of agricultural phosphorus in streams and river waters. Without data on these factors, evaluation of the feasibility of proposed control measures is speculative.

Our present estimates of the significance of agricultural phosphates in phosphorus enrichment of water are based on our knowledge of the chemistry of phosphorus in the soil, where conditons vary greatly from those in natural waters. Any interpretation of field data based on such extrapolations contains approximations that must be tested by direct observation of phosphate behavior in streams.

The primary objective can be broken down into several working objectives: (1) the identification of the sources of phosphorus entering streams and lakes; (2) the role of sediments in transporting phosphorus in moving water or acting as an adsorbent when phosphorus-deficient subsoils from streambanks enter stream channels; and (3) the development of mathematical models suitable for simulation studies on computers to evaluate the effect of fertilizer and land management practices on the phosphorus content of stream water.

Although all these working objectives are interlinked, each contains experimental problems that can be examined separately, as indicated in the following examples.

The development of sampling techniques.—Meaningful estimates of the amount of phosphorus lost require comprehensive hydrologic data, which include volume of water flow.

We need to develop sampling techniques that relate phosphorus losses to field conditons. Because extended sampling programs are expensive and often generate far more data than are needed, simple automated equipment is needed that will take proportional samples at desired intervals. Such devices would permit considerable economies on data collection and analytical work. However, the gathering of hydrologic data on the water flow at the sampling point will remain vital. Because phosphorus movement depends on runoff and erosion, it occurs sporadically. On a 300-acre farmland watershed at Coshocton, Ohio, the pattern of rainfall distribution in certain years caused as much as 80 percent of the total annual loss to take place within a single week or 10 days.

The distribution of inorganic phosphorus.—The most important problem in the behavior of the inorganic phosphorus concerns the biologically active fraction of sediment-borne phosphorus. Little is known about the distribution of the phosphorus between that in the true solution and that adsorbed on the solid particles. When sediment is derived from fertile topsoil, phosphorus availability is likely to be controlled by rate of desorption from the solid, and concentrations of dissolved phosphorus may increase. On the other hand, sediments from phosphorus-deficient material, such as subsoils, when suspended in water containing dissolved phosphate, may lower the phosphorus concentration. In this latter situation, adsorption may then drastically reduce the biologically available phosphorus below that existing in the water before sediments were introduced. Examination of the adsorption process is needed because it may be important in the removal of phosphorus from natural waters and the accumulation and stabilization of phosphorus in bottom sediments.

Studies of field situations.—Owing to the complex distribution of phosphorus (from urban as well as agricultural sources) in natural waters, we need to develop techniques for studying various patterns of phosphorus input before we can determine the most effective action to take. Computer simulation techniques, using input data on rates of soil erosion, water runoff, patterns of fertilizer application and cropping, and rates of streamflow and transport of sediment, offer considerable promise for such studies. The effects of locally intense sources of phosphorus, such as stockyards and urban communities, can easily be included in such a program. Runoff water from barnyards, hogpens, and feedlots draining directly into streams or lakes constitutes one of the most troublesome sources of agricultural phosphorus, particularly where the runoff moves over frozen ground in winter. Such runoff water has been found to contain more than 1 p.p.m. of dissolved phosphorus, which far exceeds the level required for algal growth. Research on the effectiveness of simple remedial measures, such as lagooning or ponding of barnyard wastes, is urgently required.

Summary of Phosphorus Research Needs

Our present knowledge of the chemistry of phosphorus in undisturbed field soils is inadequate for estimating the amounts of this element that move into natural waters. More chemical and hydrologic data are needed before we can isolate problem situations. We must improve our sampling techniques rather than pay for expensive monitoring programs that only provide large amounts of useless feedback.

Phosphorus movement is a complex process dominated by a set of experimentally uncontrolled variables. We need information on the effects of sediments on the movement of biologically available phosphorus; on the rate of adsorption or release of phosphorus under conditions similar to those in natural waters; and on the management of animal wastes on farms, which, at present, is the largest single agricultural source of phosphorus. Efficient application of field data to the design of remedial measures seems likely if computer simulation models were developed that could analyze the effects that changes in the sources of phosphorus will have on the overall pattern.

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